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# Spatial analysis of energy use and GHG emissions from cereal production in India

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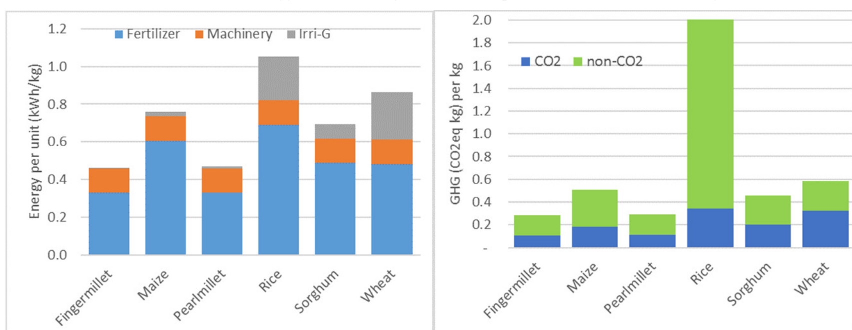
## HIGHLIGHTS

- Rice is the most energy intensive cereal in India.
- Cereals' energy use contributes 16 to 56% of their GHGs.
- Energy intensities vary spatially by up to a factor of four.
- Cereals' fertilizer use contributes 52% of their GHGs.

## GRAPHICAL ABSTRACT

Rice in India is the most energy-intensive and GHG intensive cereal. Fertilizer-related energy and emissions dominate water extraction energy, even though the latter presents localized scarcity concerns.

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## ABSTRACT

Agriculture contributes 18% of India's greenhouse gas (GHG) emissions. Yet, little is known about the energy requirements of individual crops, making it difficult to link nutrition-enhancing dietary changes to energy consumption and climate change. We estimate the energy and $CO_2$ intensity of food grains (rice, wheat, sorghum, maize, pearl millet and finger millet) taking into account their irrigation requirements, water source, dependence on groundwater, yields, fertilizer and machinery inputs.

Rice is the most energy-intensive cereal, while millets are the least. Total energy use contributes 16% of GHG emissions for rice, due to its high methane emissions, and 56% for wheat. Fertilizer production and use dominates GHG emissions from all crops, contributing 52% of GHGs from cereals. Energy intensities vary by up to a factor of four across the country, due to varying water requirements, irrigation sources and groundwater table depths. The results suggest that replacing rice with other cereals has the potential to reduce energy consumption and GHGs, though the spatial variation of production shifts would influence the extent of this reduction and the possible trade-offs with total production.



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## 1. Introduction

The intensification of agriculture in global food production has entailed disproportionately high increases in inputs, including energy. Embedded energy inputs increased by 137% in the last four decades while land use increased 10% (Pellegrini and Fernández, 2018). Although agricultural energy's share of global primary energy is still small – 1.6%, this increase is linked to a number of local environmental and social problems, related to water scarcity, energy and food security, and climate impacts. Globally, irrigated agriculture provides 40% of food production, from 18% of land (Khan and Hanjra, 2009). In many developing countries, such as China, India, Iran, Mexico and Pakistan, groundwater extraction for irrigation has expanded rapidly, often with the support of energy subsidies for agricultural pumpsets (Karimi et al., 2012; Jinxia et al., 2012; Scott, 2011; Shah et al., 2012; Siddiqi and Wescoat Jr, 2013). This has had a number of negative consequences, such as enhanced pressure on water availability for other uses (e.g., Davis et al., 2017), loss of financial viability of the electricity sector, and increased food security risks (Shah et al., 2012).

Stabilizing GHG growth for mitigating climate change is also a critical concern of global food production (Tilman et al., 2011; Lipper et al., 2014). Agriculture contributes about 10% of global GHG emissions, excluding related land-use change (Edenhofer et al., 2014). Besides livestock production (McMichael et al., 2007), rice production is a key target of mitigation in agriculture, as evidenced by the fact that it contributes 48% of cropland GHG emissions to provide 15% of total crop calories (Carlson et al., 2017). The importance of understanding local crop management practices in global climate mitigation studies has been increasingly recognized as important (Carlson et al., 2017). This is no truer than for global rice production, almost half of which is contributed by the smallest farms (<2 ha) (Pellegrini and Fernández, 2018).

India is a critical locus of these local and global challenges of the agricultural sector, and in particular of rice cultivation. India is the world's leading emitter of rice-generated methane (27%), is the second-largest consumer of rice after China, contributes 22% of global rice production, and is the world's largest rice exporter (Carlson et al., 2017; FAOSTAT, 2018). At the same time, India is under pressure to expand food production and availability to provide adequate nourishment to its growing population. India is home to almost a quarter of the over 800 million people who are undernourished in the world, and an even greater number who lack essential vitamins and minerals (FAOSTAT, Muthayya et al., 2013). The spread of high-yield varieties of rice has displaced more nutritious coarse cereals, such as millets and sorghum (DeFries et al., 2015), thereby exacerbating malnutrition (e.g., DeFries et al., 2018). Recent research has shown that a shift from rice to these coarse cereals can improve nutrition and reduce non-$CO_2$ GHG (Rao et al., 2018).

Surprisingly, little is known about the energy requirements and related $CO_2$ emissions impacts of individual grains cultivated in India. This makes it difficult to compare different grains in terms of their broader health and environmental impacts, including nutritional impacts, climate change and local water stress. Global studies of food security increasingly point to the importance of these linkages (Bajželj et al., 2014; DeFries et al., 2015; Carlson et al., 2017). They enable viewing environmental sustainability in conjunction with and as an outcome of development policies in developing countries. In this study, we fill this gap by estimating the energy and $CO_2$ intensities of food grains, or cereals, and their spatial variation taking into account irrigation requirements, dependence on groundwater, yields and embedded energy in fertilizer inputs. We combine these estimates with known non-$CO_2$ emissions, methane and $N_2O$ (Rao et al., 2018), to compare the energy and emissions impact of different cereals and to draw inferences for food and climate policy.

## 2. Background

India's agricultural sector contributes 4.2% of India's energy use and 18% of India's GHGs (INCCA, 2010), which is well above the global average of 1.6% for energy and 12% for GHG (Pellegrini and Fernández, 2018). This is despite having a relatively low, in absolute terms, energy density of crop production in comparison to other countries (Ghisellini et al., 2016). Mechanization has been steadily increasing energy intensity in the last decades (Jha and Singh, 2012).

Cereals are the source of more than half of total calorie consumption of Indians, and more so for lower income populations (Srivastava et al., 2013). Cereals comprise 47% of total crop production, or 51% if rice were weighed as paddy. Because grain production and consumption are so tightly linked, the Green Revolution (GR) altered the composition of cereals consumed in India by introducing high-yield varieties of rice and wheat that gradually replaced traditional coarse cereals (including millets, maize, and sorghum) (DeFries et al., 2015). The proportion of coarse cereals in total cereals has declined from 35% to 5% in rural India between 1961 and 2014 (DeFries et al., 2018). Research on the consequences of this shift for nutrition, water resources and other environmental consequences is limited, but has been growing (Rao et al., 2018; Davis et al., 2018; DeFries et al., 2018).

Agricultural GHG emissions reporting in India is split across the energy and agriculture sectors, which complicates comprehensive assessments of the climate change impacts of food consumption. India's emissions report to the UN Framework Convention on Climate Change (UNFCCC) reports energy use in agriculture only implicitly in energy-sector emissions, while agricultural emissions include only non-$CO_2$ emissions, such as methane from rice and livestock and nitrous oxides from fertilizers. The FAO also reports that $CO_2$ emissions from Indian agriculture contributed 17% of the country's total GHG emissions (FAOSTAT). However, this excludes fertilizer imports, which comprise about 30% of fertilizer use in India.

Irrigation has also been studied extensively in the context of groundwater depletion and water scarcity (Brauman et al., 2016; Wada et al., 2012). In India in particular, unsustainable groundwater depletion is likely driven by irrigation, which accounts for 90% of groundwater withdrawal (CGWB, 2017). Sixty-four percent of the net irrigated area (counting area cultivating more than one crop per year once) is watered from groundwater (Agricultural Census of 2010–2011, 2015). Irrigation contributes 38% of energy used for agricultural production (Fig. 1).

Irrigation's dependence on groundwater has been increasing since the seventies due to the provision of free electricity for pumping to farmers. This has resulted in gross inefficiencies in water use. In 2001, 88% of farmers irrigated crops by flooding through open channels (Fishman et al., 2015). Several studies have examined the potential for improvements in irrigation efficiency, both globally (Zhang et al., 2014; Campana et al., 2017) and for India (Fishman et al., 2015; Patle et al., 2016). However, Fishman et al. (2015) concluded that the constraint to such improvements is more related to incentives than knowledge or technology. In the electricity sector, improving pumpset efficiency has been a priority for states and electric utilities (IEI, 2010). The national government launched the National Energy Efficient Agriculture Pumps Programme in 2016, which aims to achieve a 30% reduction in energy use by pumps replaced by this program by 2019.

In the few studies that do examine crop-specific energy and emissions in India, some estimates can be found, but these are for only some cereals and for some components of GHGs. Vetter et al. (2017) estimated GHG intensities of production for rice and wheat, but lump other cereals into a single category. Their estimates do not appear to take into account spatial variations in groundwater availability. Patle et al. (2016) estimated $CO_2$ emissions from rice, wheat and pearl millet, but for one district in one state of India. A few studies have estimated methane emissions for rice (Yan et al., 2003) and livestock (Gerber et al., 2013). Rao et al. (2018) estimate total non-$CO_2$ emissions for all cereals, but not energy-related emissions.

What we do understand about cereals' energy consumption is that, in aggregate, rice and wheat rely far more than other cereals on irrigation, namely for 65 and 86% of cultivated area respectively (See Table 1). Coarse cereals are mostly rain fed. Only 10–11% of cultivated

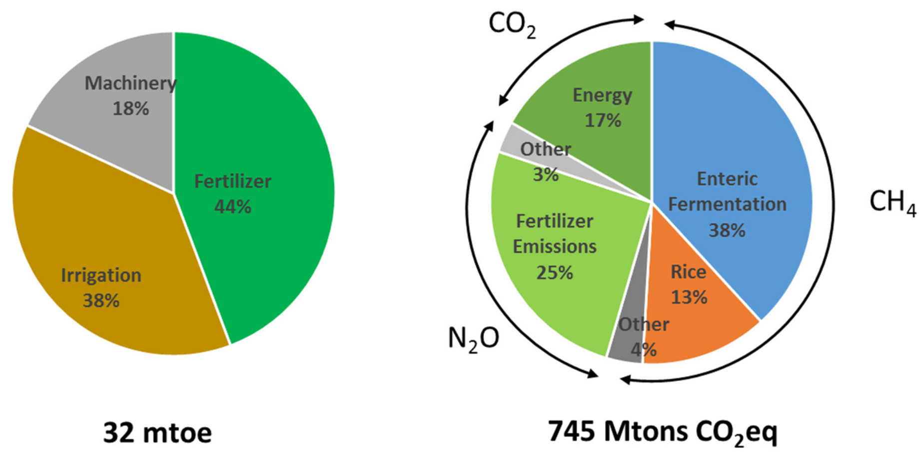


**Fig. 1.** Energy and GHG emissions for agricultural production in India. Excludes fertilizer imports, food processing and transport. Data on energy: Author calculations (see Data section). Emissions: FAOSTAT, Food and Agricultural Organization. 'Other' for $N_2O$ includes emissions from crop residues and burning. 'Other' for $CH_4$ includes emissions from manure management and burning. Energy-related $CO_2$ includes emissions from fertilizer production, irrigation and machinery use.

area of millets and sorghum is irrigated. Rice also has the highest fertilizer inputs, and the millets the lowest, but the other grains are comparable. Thus, it is likely that rice and wheat would have higher energy consumption per unit of land cultivated. However, rice and particularly wheat have higher yields, which can offset the effect of higher input requirements. What is not known is the relative energy intensities of cereals per unit of production considering all these factors when grown in the same region, nor their aggregate energy intensity considering their different spatial patterns of production. The spatial patterns matter because of the large variation across the country in not only climatic conditions, but also in geological conditions (e.g., water table depths) (Fig. 2), on which irrigation has increasingly relied.

In this paper, we estimate energy consumption and $CO_2$ emissions and their spatial variation across the country for cereal cultivation, including direct energy at the farm-level and energy embedded in fertilizer inputs. This includes energy for pumping groundwater, fertilizer production and operating agricultural machinery. An important contribution of the analysis is to reveal the spatial heterogeneity in the cereals' energy intensity due to varying groundwater depth, at the district-level, and fertilizer intensity, at the state level. We conclude by drawing inferences for the environmental implications of future food security policies.

## 3. Data

We rely almost entirely on publicly available data sets provided by different government ministries based on various surveys (Table 2). We draw on expert knowledge to estimate the shares of different uses of energy for agriculture, because these data are not typically compiled, as discussed earlier. We applied expert judgment to data from several different ministries and sources. Downstream energy for transport and food-processing and the energy embedded in fertilizer imports are excluded, because we do not know their distribution across crops or their mode of production.

Our calculations are based in districts, which include 261 of the 311 districts defined in the Village Dynamics in South Asia survey (VDSA) (based on district definitions in the sixties). These districts contribute ~195 million tonnes of cereal production out of an actual total of 213 million tonnes (or 268 m tonnes, where rice is measured as paddy). Table 2 shows the key variables, their data sources, and their spatial granularity.

The 'blue' (irrigation) crop water requirements (CWR) are obtained from Davis et al. (2018), whose methodology is detailed in the SI. These values – calculated daily and then aggregated over the entire growing season – represent the supplemental irrigation required to make up any shortfall when rainfall amounts are less than the amount of water required for soil moisture to remain above a crop's wilting point. The study provides 2000–2009 averages, to smooth out climate-driven volatility in water requirements. We differentiate yields for rainfed and irrigated crops, but do not have the data to differentiate yields for surface- vs groundwater-irrigated cultivation.

**Table 1**
Key production characteristics influencing energy intensity of cereals, 2010. Irrigated share of cultivated area from the Agricultural Census of India 2010–11. See Table 2 for other data sources.

| Cereal | Total production | Fertilizer input | Irrigated share of cultivated area |
|---|---|---|---|
| | (Mil. Tons) | (kgN/ton) | (%) |
| Finger millet | 7 | 28 | 10% |
| Maize | 22 | 52 | 25% |
| Pearl millet | 7 | 28 | 10% |
| Rice (paddy) | 90(144) | 59 | 65% |
| Sorghum | 7 | 42 | 11% |
| Wheat | 81 | 41 | 86% |

## 4. Methods

Energy consumption for crop cultivation includes direct energy to pump water and power machinery, such as tractors, and indirect energy for manufacturing fertilizers. The breakdown of agricultural energy use by function (irrigation, machinery use and fertilizer) had to be triangulated from a number of different sources of retail sales, since fuel use for agriculture in particular is not tracked by government (See Supplementary material). For instance, the majority of electricity use for agricultural pumpsets is not metered, but estimated by electric utilities based on pump size. Diesel use is not known by state, but its breakdown for agricultural machinery and irrigation pumping was estimated based on a market survey of diesel use commissioned by the Ministry of Petroleum & Natural Gas in 2012 (See Supplementary material). Given data on aggregate energy use, our focus was on estimating the relative energy intensities of cereals considering their inputs and spatial production patterns.

We used different approaches for each energy use (machinery, fertilizer manufacturing and irrigation) to allocate aggregate energy to cereals, based on the corresponding input requirements, which were available at different levels of spatial granularity. For machinery, for which we had no crop-specific input data, we allocated the fuel use to cereals in proportion to their production (assuming the same use for rain fed and irrigated areas). Fertilizer use per unit of cultivated area was available state-wise by crop and by water source (irrigation vs

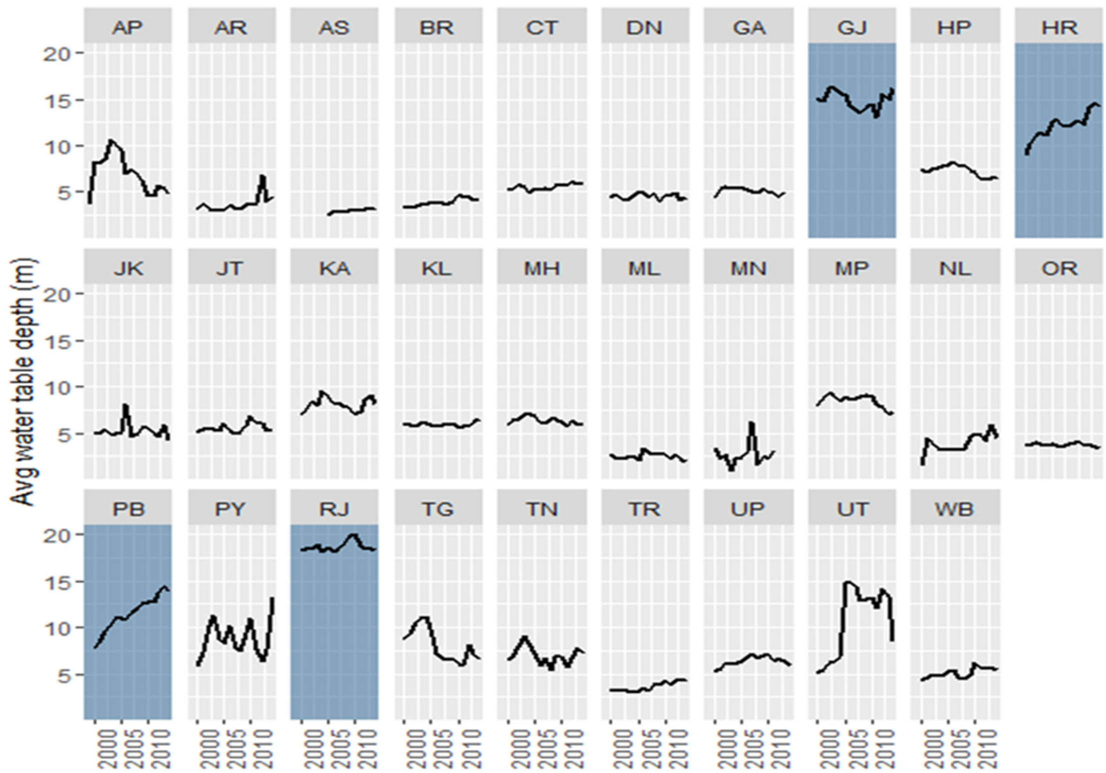


**Fig. 2.** Groundwater depth, average by state, 2000–2014. Data: Central Groundwater Board, Ministry of Water Resource. See Table 2 for details. Highlighted states have intensive agriculture and the lowest water tables (GJ: Gujarat; RJ: Rajasthan; PB: Punjab; HR: Haryana).

rain fed). We combined these with yields to estimate fertilizer intensity per unit of production by crop and water source. Among the typical fertilizer inputs of nitrogen, potassium and phosphorous, urea production for nitrogen dominates fertilizer energy use (Dept of Fertilizers, 2013). Since the urea production process is fairly standard, we assumed a fixed energy intensity of urea production and allocate aggregate fertilizer energy to crops state-wise, in proportion to their nitrogeneous fertilizer intensity.

The energy intensity (kWh per unit of production, kg) of any crop $i$ in district $j$ by water source $k$ (irrigated or rainfed) is given by the sum of the three components (Eqs. (1a) and (1b)): pumping energy for irrigated areas only by crop and district; fertilizer energy intensity by crop and water source and state $s$; and machinery use, a constant. For irrigated areas, this is given by:

$$e_{irr,i,j} = e_{pump,irr,i,j} + e_{fert,irr,i,s} + e_{mach} \tag{1a}$$

The corresponding energy intensity for rainfed areas is:

$$e_{rain,i,j} = e_{fert,rain,i,s} + e_{mach} \tag{1b}$$

Irrigation energy is the most challenging and spatially heterogeneous, due to the use of different water sources (rain fed, irrigated surface and irrigated groundwater). Here we allocated aggregate irrigation energy to cereals based on the physical requirements for pumping water by district, based on each crop's CWR (volume of water per unit area, $m$), and accounting for the share of groundwater vs surface irrigation, the groundwater depth, and crops' yields, all three by district, as described further below.

We aggregated the results for each component to a weighted average energy intensity per cereal, weighted by production for irrigated and rain fed cultivation (Eq. (2)). The overall energy intensity of each

**Table 2**
Data sources. All energy statistics pertain to the agricultural sector of India. ICRISAT: International Crops Research Institute for the Semi-arid Tropics.

| Variable | Unit | Data source | Granularity |
|---|---|---|---|
| Crop yield | Tons/ha | Village Dynamics in South Asia (VDSA), ICRISAT – includes crop (total) area and production. Irrigated area production and yield available but not reliable. | District |
| Crop yield by water source (rainfed/irrigated) | Tons/ha | Estimation by authors using Cost of Cultivation farm survey, Director of Economics and Statistics, Ministry of Agriculture. | District |
| Groundwater level | m | Central Groundwater Board, Ministry of Water Resource. Obtained from Benjamin Clark, Columbia University. | Sub-district, 29,000 sample, quarterly |
| Irrigation crop water requirements (CWR) | mm/yr | Davis et al. (2018). Accounts for rainfall, temperature, soil conditions, and evapotranspiration. | District, 2000–2009 avg |
| Surface vs groundwater shares | Percent (of net irr area) | Village Dynamics in South Asia (VDSA), ICRISAT – Irrigation sources (dt_sia_a_web.xls). | District, annual |
| Fertilizer input, by crop, by water source (irrigated/rain fed) | Tons/ton | Dept. of Agriculture and Conservation (DAC), Input survey database, Table 4 (inputsurvey.dacnet.nic.in/nationaltables.aspx). | State-level, annual |
| Total agriculture energy use and breakdown | mtoe | Estimation by Prayas energy group (includes fertilizer manufacturing, irrigation, and machinery). See Supplemental Material for details. | National, annual (2009–10) |

crop, therefore, depends significantly on the spatial pattern of production.

$$e_i = \sum_{\forall j,k} e_{k,i,j} p_{k,i,j} \tag{2}$$

We estimated $CO_2$ emissions from energy use based on fuels' carbon content and the electricity mix in India (See Supplementary material for details). Farmers use both diesel and electric pumps, the energy consumption of which is not known in any public data source. However, based on available data on electricity retail sales, we estimated the share of irrigation energy from electricity in the handful of states in Northern and Eastern India where diesel use is concentrated. We added the non-$CO_2$ GHG emissions (methane for rice and nitrous oxide from fertilizer use for all crops) from Rao et al. (2018) to calculate the total GHG per unit of production of the six cereals. Our base calculations are for 2010.

### 4.1. Irrigation energy pumping requirements

The irrigation pumping energy for rain fed and canal-irrigated crops is assumed to be zero. For areas with pumped groundwater, we used basic physics to estimate the energy (kWh) required to lift a mass ($CWR_{i,j}$ x density, ρ, kg/m$^3$) of water a certain height (the groundwater depth, $h_j$) to overcome gravity ($g$) per hectare of cultivated land (Eq. (3)). When combined with the yield ($y_{irr,i,j}$ in kg per hectare), this gives the energy intensity per unit of production. This approach is similar to that used in the IMPACT-WATER model (Zhu et al., 2007) and by Patle et al. (2016). However, this is a theoretical requirement, since there are pumping and other system efficiency losses in getting water to the crops. Since these efficiencies are not known, we assumed they are on average the same and estimate the efficiency scalar, $K$, that, when applied to these intensities and combined with production, yields the known aggregate energy use (Eq. (4)). The CWR is crop- and district-specific, but the groundwater depth and share of cultivated area that is irrigated with surface vs groundwater are known by district, but not by crop. Due to this data limitation, the implicit assumption in the analysis is that all crops grown in a particular district have the same share of groundwater-irrigated cultivated area and the same groundwater depth. The groundwater data have a number of observations per district, but they are not associated with any specific crop or farm. We therefore used the median groundwater depth per district (see SI for a map), as the mean is skewed by outliers.

For each crop $i$, district $j$, the pumping energy intensity $e_{pump,i,j}$, kWh per kg, for irrigated areas is given by:

$$e_{pump,irr,i,j} = (CWR_{i,j} \times \rho) \times g \times h_j \times y_{irr,i,j} \times Grd.Shre_j \times {}^1/_K \tag{3}$$

where $hj$ is the median district groundwater depth, $g$ is the gravitational constant, and $Grd.Shre_j$ is the percent of cultivated area by district that is groundwater irrigated. $K$ is an efficiency scalar that, given production amounts $p_{i,j}$ on irrigated areas for crop $i$ in district $j$, relates the energy intensities to total irrigation pumping energy $E_{pump}$ as follows:

$$E_{pump} = \sum_{i,j} e_{pump,irr,i,j}\, p_{i,j} \tag{4}$$

## 5. Results

We first present some descriptive results of crop characteristics with respect to water usage and how they help explain the irrigation energy intensity results. Table 3 shows the weighted average water usage characteristics of crops, which reflects their intrinsic water requirements and productivity, district hydrological characteristics, and the spatial pattern of production across districts. The key message is that the crops differ from each other with respect to the patterns they exhibit for each of these drivers, thereby providing no clear intuition for their relative energy intensities. Note also that the aggregate energy impact of crops is further mediated by the extent to which the cereals are irrigated in the first place. As discussed earlier, in the case of coarse cereals, particularly the millets and sorghum, only a small share is currently irrigated. The energy intensity results we present, therefore, matter more for their potential scale-up in the future rather than to explain current agricultural energy use.

With respect to crop water requirements (CWR) and yields, the cereals fall into two groups: rice, wheat and maize have high CWR and the highest yields; while sorghum and the millets have lower CWR (by an order of magnitude, in the case of the millets) and moderately lower yields. Both these characteristics offset each other to an extent. The difference in overall CWR between rice and the coarse cereals reduces slightly when we compare them only in rice-growing districts (Column 3). This suggests that the difference in water requirements between them is only in small part due to differences in the geographic conditions in which they grow. The energy intensity of water extraction depends further on water table depth. Pearl millet (known as 'Bajra' in India) is grown in Rajasthan, a partially desert state with the deepest water table. However, only 15% of irrigated area uses groundwater (Table 3), and just 1–3% of cultivated area is irrigated (Table 1). Wheat relies for about a quarter of its production on relatively deep water tables, in Punjab and Haryana (Fig. 2). The remaining cereals rely on comparable water table depths.

The one factor that influences all the above indicators is crop production patterns, which, like water table depth, vary widely between crops (Fig. 3). Aside from maize, the bulk of the other cereals' production is relatively concentrated in a few states that are in different parts of the country: rice in pockets of the north and south; wheat in the north and Northwest; sorghum in central India; pearl millet in Rajasthan and Gujarat; and finger millet in Karnataka. These patterns confirm that overall irrigation energy intensity depends very much on locational hydrological and climate conditions.

**Table 3**
Key cultivation conditions influencing energy intensity of cereals' water requirements. District-wise data, weighted by production by season. Share of groundwater (vs surface) irrigated area is available by district, not by crop. All data are for 2010 except CWR, which is an average for 2000–09. See Table 2 for data sources.

| Cereal | (1) Water table depth | (2) Crop water requirement (CWR) | (3) CWR rice-growing districts | (4) Yield | (5) Groundwater share of irrigation | (6) Irrigated share of total production |
|---|---|---|---|---|---|---|
| | (m) | (m) | (m) | (ton/ha) | (%) | (%) |
| Finger millet | 6.9 | 0.6 | 0.7 | 2.1 | 38% | 8% |
| Maize | 6.3 | 3.1 | 3.4 | 3.0 | 37% | 30% |
| Pearl millet | 21.1 | 0.5 | 0.3 | 1.4 | 15% | 5% |
| Rice | 5.8 | 9.9 | 9.9 | 2.7 | 54% | 70% |
| Sorghum | 5.6 | 2.2 | 2.6 | 1.7 | 37% | 61% |
| Wheat | 9.2 | 5.3 | 5.1 | 3.6 | 29% | 100% |

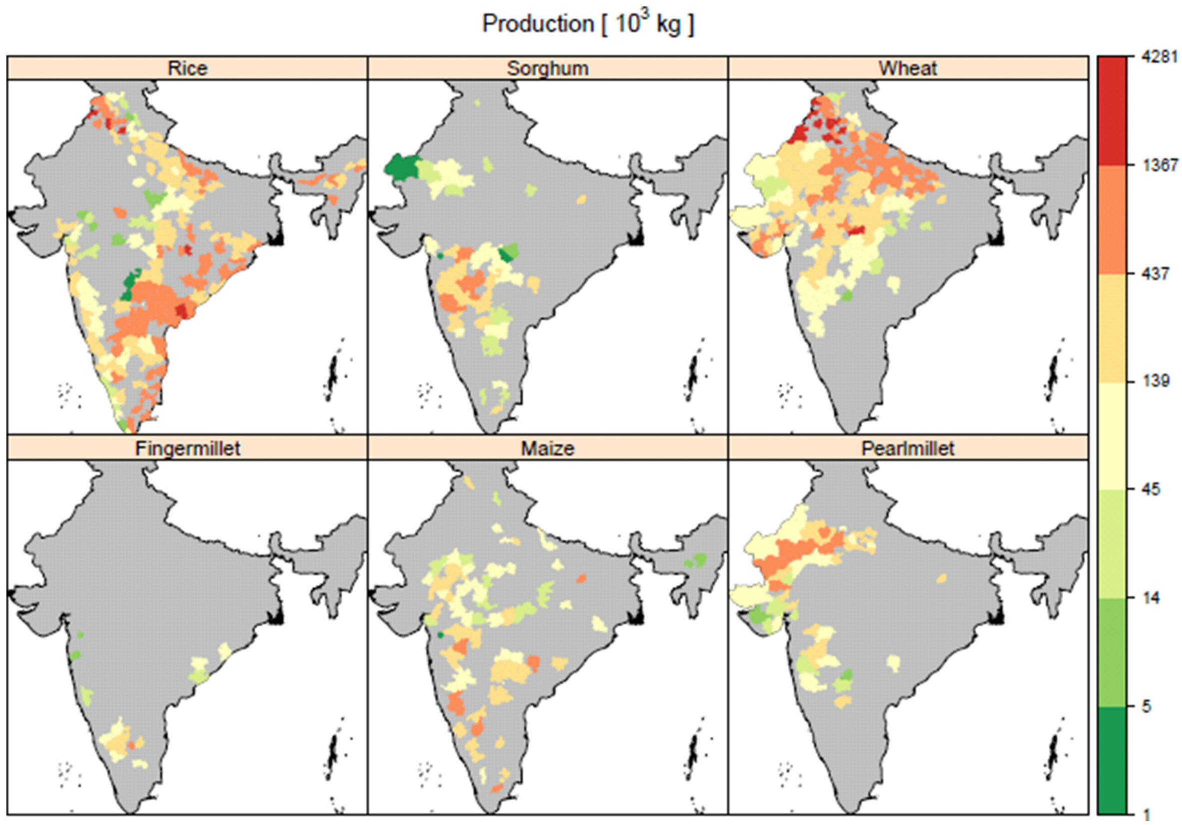


**Fig. 3.** Crop (total) production spatial patterns in India in 2010 for 261 of 311 districts defined in the Village Dynamics in South Asia survey (those having data on crop production, groundwater depth and groundwater share of irrigation). See Table 2 for data sources.

The net result of the various drivers discussed above is shown in Fig. 4a,b. Rice has the highest (weighted average) energy intensity with 1.1 kWh/kg, followed by wheat and maize, with 0.9 kWh/kg and 0.8 kWh/kg respectively. The millets have the lowest energy intensity of 0.5 kWh/kg, less than half that of rice. Energy for fertilizer inputs dominates crop energy use, comprising 56% (for wheat) to 80% (for maize) of total energy intensity. Rain-fed areas consistently have lower energy needs, mainly because they have less fertilizer inputs, and also no pumping energy requirements. The irrigation energy share, considering all forms of production, is highest for wheat at 30% (Fig. 4a). This is because wheat is grown in the 'rabi' (or winter) season when there is little rain, and wheat is cultivated in Haryana and Punjab, where the water table is low and dropping (Fig. 2). Rice has the next highest irrigation share at 22%, due also to its relatively high production in states with low water tables such as Punjab. In absolute terms, pearl millet cultivation in Rajasthan has the highest irrigation energy intensity of ~1.1 kWh/kg, due to very low water tables (Fig. 2). However, <5% of pearl millet's production comes from Rajasthan.

Note that we present the average of the energy intensity between groundwater- and surface water-based irrigation. In reality, the energy intensity for groundwater-irrigated cultivation is likely to be lower than this average, because farmers have greater control over the timing and quantity of irrigation with groundwater irrigated crops. Conversely, surface-water irrigated areas would have lower yields than the average assumed, and therefore higher than shown energy intensities.

From a GHG perspective, fertilizers contribute 52% of cereals' emissions including methane, and about 71% without. Fertilizer emissions include both $CO_2$ emissions from manufacturing and $N_2O$ emissions from their use (Fig. 4b). $CO_2$ emissions comprise 16% (for rice) to 56% (for wheat) of total GHG emissions. $CO_2$ emissions intensities are roughly proportional to energy consumption, except to the extent that the share of electricity (vs diesel) use in irrigation pumps differs. The carbon intensity of electricity is almost triple that of diesel because of coal use and multiple energy conversion stages. For instance, rice and wheat have comparable $CO_2$ emissions even though rice has higher overall energy use, because rice cultivation employs a lower share of electric pumpsets. Besides rice, other crops' $CO_2$ emissions are comparable in magnitude to the $N_2O$ emissions from fertilizers. The GHG emissions gap between rice and the other crops is due to its methane emissions.

The spatial variation of energy intensity (Fig. 5) is by and large in inverse proportion to crops' production intensity. That is, in general, for all crops the areas with the most intense production (redd-ish areas in Fig. 3) have relatively low energy intensity (pale yellow to green in Fig. 5), which is somewhat comforting. Rice production in Punjab, among other spots, is a notable exception, where rice production is significant and dependent on deep water tables.

Based on this spatial pattern of energy intensities and water requirements, the effective system efficiency ($K$ in Eq. (3)) that yields the total reported irrigation energy is approximately 43%. Note that this is the product of pump efficiency and irrigation system efficiency. This can be compared to some rough figures at the national level. Pumpset efficiencies have been extraordinarily low, between 20 and 30% (Dixit and Sant, 1996; Singh, 2009), and new ones in India apparently are rated at 40–50% efficiency.[1] However, internationally agricultural pumpsets are typically 70–90% efficient. This implies that the efficiency of water delivery for cereals may be considerably higher than for other crops in India. However, there is considerable uncertainty surrounding the aggregate energy figures, so this result is not as robust as the relative variation of energy use across crops and space.

[1] Press release, Ministry of Power: http://pib.nic.in/newsite/PrintRelease.aspx?relid=128572, retrieved on October 13, 2018.

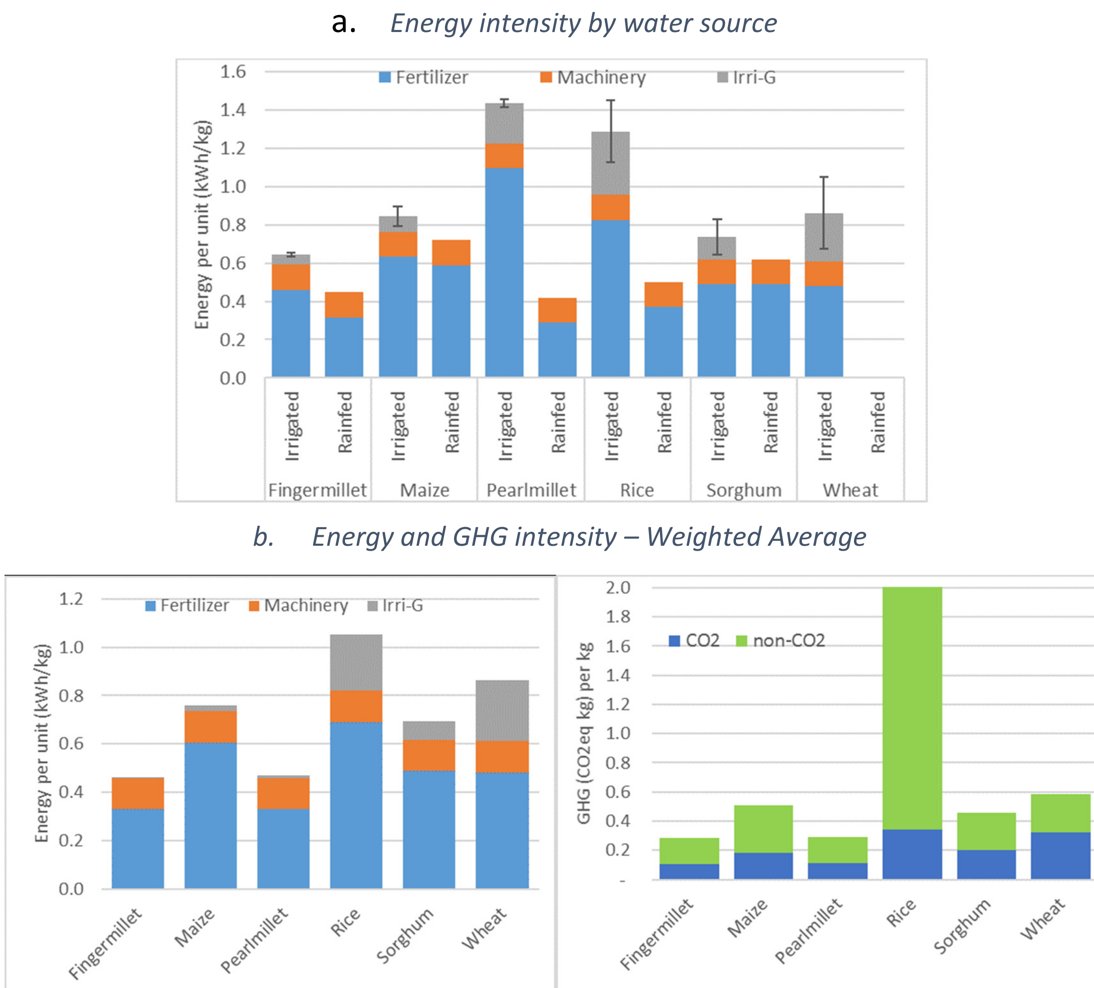


**Fig. 4.** Energy intensity and total GHG emissions of cereals in 2010, (a) by water source, and (b) weighted by production shares in each water source (Table 3, Col. 6). Error bars show one median absolute deviation (MAD) around median groundwater depth. Non-$CO_2$ intensities from Rao et al. (2018) include nitrous oxide ($N_2O$) from fertilizers and methane ($CH_4$) from rice cultivation only. Note: For sorghum, rain fed and irrigated fertilizer were assumed to be the same, due to unreliable data. Irrigated is a district-wise weighted average of surface- and groundwater-irrigated cultivation.

## 6. Discussion

We find overall that rice is the most energy-intensive cereal, followed by wheat. This supports previous studies' findings that rice has the highest environmental impacts among cereals, but we demonstrate this for the first time for energy consumption. The expansion of rice cultivation area since the Green Revolution has come in part at the expense of coarse cereals, particularly sorghum cultivation, which has likely led to an increase in the energy intensity of agricultural production. There is large variation in energy intensity among the other cereals. Wheat, sorghum and maize have comparable energy intensities, and the two millets have the lowest energy intensities, about half that of rice.

A key finding is that fertilizer manufacturing dominates the energy intensity and total GHG emissions for all crops, from energy consumed in their manufacturing ($CO_2$ emissions) and from their use ($N_2O$ emissions). The irrigation energy share of total GHG is relatively small (1–13%) for all crops except wheat (32%). This, coupled with the fact that fertilizer energy use in agriculture exceeds that of irrigation (Fig. 1), suggests that from a climate perspective promoting judicious fertilizer use or improving the energy efficiency of its production may have more potential than reducing irrigation energy consumption. However, the importance of irrigation energy is that it is dominated by rice and wheat production, in particular in northern states. Focused efforts on farming practices can have significant benefits for energy and water. Shifts away from rice production, in particular, have the additional climate benefit of reducing methane ($CH_4$) emissions.

That both inputs and yields are high for rice and wheat raises the question as to whether the former are the price to pay for accelerated production. The high spatial variation of energy intensity suggests that it is not clear whether this correlation between inputs and yield hold consistently across the country. We have observed that energy intensities vary widely across the country. To examine this in greater detail, we plotted the energy intensity against yield for all crops grown in all districts in the analysis (Fig. 6).

This representation shows that for all crops energy intensities fall within a narrow band (factor of two) compared to yields, which vary by up to a factor of four. However, there is a relatively large cloud of rice-, and to a smaller extent wheat-, growing districts with above average yields and a higher range of energy intensities. Of these, the rice-growing districts with the largest production are mostly in Punjab, Haryana and Andhra Pradesh, and the wheat in Rajasthan. Most notably, there is not much production, but for a few outliers, in the upper left quadrant, namely with high energy intensity but low yields. This confirms the general rationality in production patterns, from an energy perspective. This further implies that although shifts away from rice production can have significant environmental benefits, as the volume of these shifts increases, aggregate production may be traded off. This trade-off merits more systematic investigation in further research.

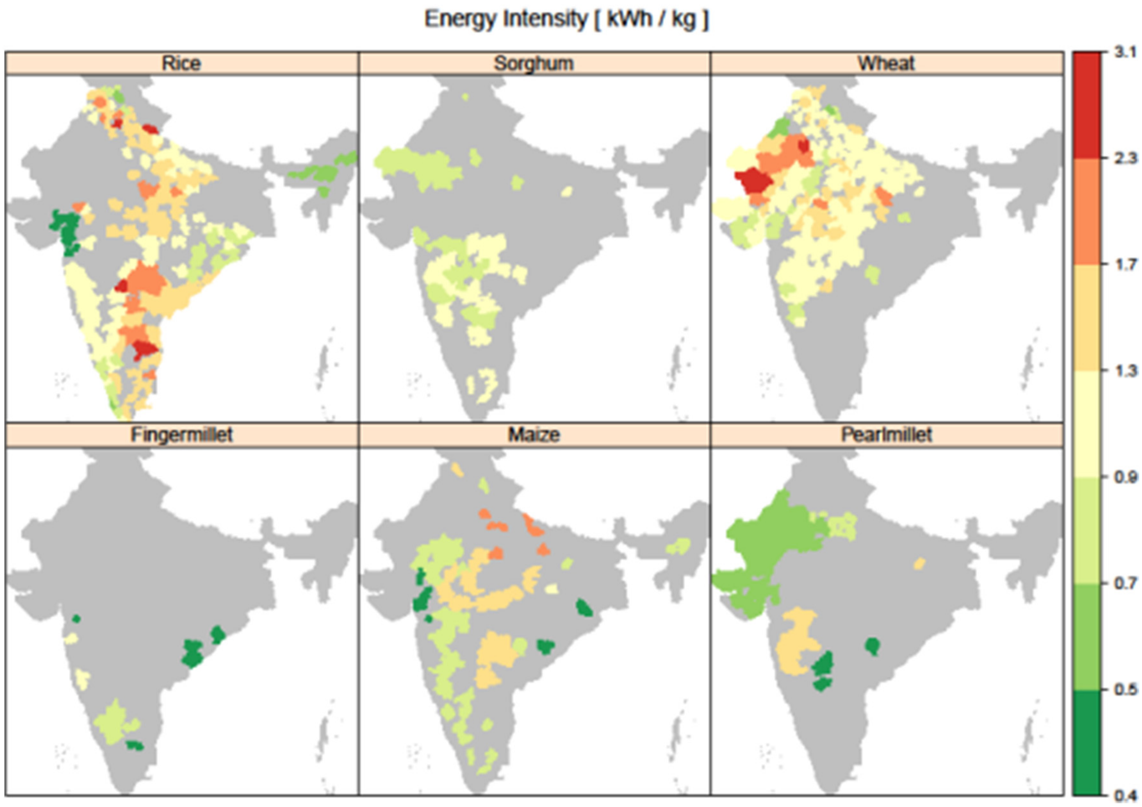


**Fig. 5.** Spatial distribution of energy intensity by crop (average weighted across all water sources) for districts included in the analysis (261 of 311 districts defined in the Village Dynamics of South Asia (VDSA) survey). See Table 2 for data sources.

This study was conducted with data limitations. The shares of surface- vs groundwater-irrigated production were known only by district, but not by crop. Local knowledge of water sources would enable more informed decisions about crop substitution and resource requirements. Future studies should also assess the effects of water sources on irrigation efficiency, farmers' cropping patterns and other factors that influence the overall energy intensity of production. Data on fertilizer imports and their relative use by cereals were also unavailable.

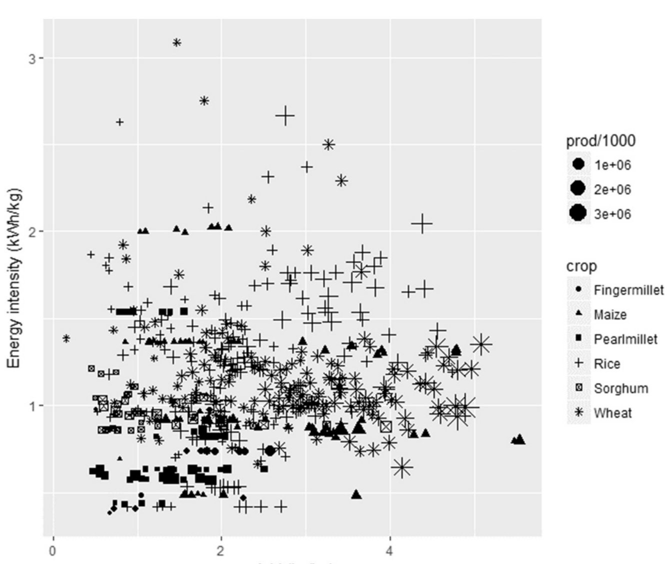


**Fig. 6.** Energy intensity (kWh/kg) by crop (average weighted across all water sources) against yield (kg/ha) for districts included in the analysis (261 of 311 districts defined in the Village Dynamics of South Asia (VDSA) survey). Tick mark sizes reflect production levels.

## 7. Conclusion

Milled rice has the highest energy intensity of production. In addition to methane emissions from rice cultivation, the primary source of GHGs for all cereals is fertilizer manufacturing and use. Irrigation energy contributes substantial $CO_2$ emissions for wheat and rice only.

Energy intensities of cereals differ spatially due to varying water requirements and yields, and their corresponding production patterns. Rice and wheat production in Northern India is potentially a hot spot of concern, since it feeds a significant portion of the country, and depends heavily on electricity for irrigation, in regions where the water table is rapidly declining. Otherwise, the pattern of cultivation, in general, reflects production intensities that correlate inversely to energy intensity. Nevertheless, due to differences in energy intensity between crops and across regions, different mixes of cereal production offer promise for reducing overall energy consumption and GHG emissions. However, the scope for this reduction needs to be investigated based on feasible scenarios of shifts in production patterns.

This study has revealed the importance of examining spatial heterogeneity in crop production patterns and their environmental impacts. This type of comparative analysis of crop production at high spatial granularity can help identify hot spots in other large countries with groundwater dependence, such as China and Mexico, where the trade-offs between consumption-side benefits and production-side environmental impacts can be examined.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.11.073.

## References


Bajželj, Bojana, et al., 2014. Importance of food-demand management for climate mitigation. Nat. Clim. Chang. 4 (10), 924.

Brauman, Kate A., et al., 2016. Water depletion: an improved metric for incorporating seasonal and dry-year water scarcity into water risk assessments. Elem. Sci. Anth. 4.

Campana, P.E., et al., 2017. Suitable and optimal locations for implementing photovoltaic water pumping systems for grassland irrigation in China. Appl. Energy 185, 1879–1889. https://doi.org/10.1016/j.apenergy.2016.01.004.

Carlson, Kimberly M., et al., 2017. Greenhouse gas emissions intensity of global croplands. Nat. Clim. Chang. 7 (1), 63.

CGWB, 2017. Dynamic ground water sources of India. Central Ground Water Board, Ministry of Water Resources, Government of India.

Davis, K.F., Rulli, M.C., Seveso, A., D'Odorico, P., 2017. Increased food production and reduced water use through optimized crop distribution. Nat. Geosci. 10, 919–924.

Davis, K.F., Chiarelli, D.D., Rulli, M.C., Chhatre, A., Richter, B., Singh, D., DeFries, R., 2018. Alternative cereals can improve water use and nutrient supply in India. Sci. Adv. 4 (7), eaao1108.

Defries, R.F. Jessica, Remans, Roseline, Palm, Cheryl, Wood, Stephen, Anderman, Tal L., 2015. Metrics for land-scarce agriculture. Science 349 (6245), 238–240.

DeFries, Ruth, et al., 2018. Impact of historical changes in coarse cereals consumption in India on micronutrient intake and anemia prevalence. Food Nutr. Bull. 39 (3), 377–392.

Department of Fertilizers, 2013. Indian Fertilizer Scenario 2013. Ministry of Chemicals and Fertilizers, Government of India.

Dixit, S., Sant, G., 1996. Agricultural pumping efficiency in India: the role of standards. Energy Sustain. Dev. III (1), 29–37.

Edenhofer, O., et al., 2014. Technical Summary. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

FAOSTAT, 2018. Online Statistical Service Food and Agriculture Organization (FAO). http://faostat3.fao.org.

Fishman, R., Naresh, D., Swaminathan, R., 2015. Can improved agricultural water use efficiency save India's groundwater? Environ. Res. Lett. 10, 084022.

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., Tempio, G., 2013. Tackling Climate Change Through Livestock – A Global Assessment of Emissions and Mitigation Opportunities. Food and Agriculture Organization of the United Nations (FAO), Rome.

Ghisellini, P., Setti, M., Ulgiati, S., 2016. Energy and land use in worldwide agriculture: an application of life cycle energy and cluster analysis. Environ. Dev. Sustain. 18 (3), 799–837.

IEI, 2010. Efficient well-based irrigation in India: compilation of experiences with implementing irrigation efficiency. International Energy Initiative, Asian Regional Initiative, Bangalore, India.

INCCA, 2010. India: Greenhouse Gas Emissions 2007. Indian Network for Climate Change Assessment. Ministry of Environment and Forests, Government of India.

Jha, G.K.P. Suresh, Singh, Alka, 2012. Changing energy-use pattern and the demand projection for Indian agriculture. Agric. Econ. Res. Rev. 25, 61–68.

Jinxia, W., et al., 2012. China's water–energy nexus: greenhouse-gas emissions from groundwater use for agriculture. Environ. Res. Lett. 7, 014035.

Karimi, P., Qureshi, A.S., Bahramloo, R., Molden, D., 2012. Reducing carbon emissions through improved irrigation and groundwater management: a case study from Iran. Agric. Water Manag. 108, 52–60. https://doi.org/10.1016/j.agwat.2011.09.001.

Khan, S., Hanjra, M.A., 2009. Footprints of water and energy inputs in food production – global perspectives. Food Policy 34, 130–140. https://doi.org/10.1016/j.foodpol.2008.09.001.

Lipper, L., et al., 2014. Climate-smart agriculture for food security. Nat. Clim. Chang. 4, 1068–1072.

McMichael, A.J., Powles, J.W., Butler, C.D., Uauy, R., 2007. Food, livestock production, energy, climate change, and health. Lancet 370, 1253–1263.

Muthayya, S., Rah, J.H., Sugimoto, J.D., Roos, F.F., Kraemer, K., Black, R.E., 2013. The global hidden hunger indices and maps: an advocacy tool for action. PLoS One 8 (6), e67860.

Patle, G.T., Singh, D.K., Sarangi, A., Khanna, M., 2016. Managing $CO_2$ emission from groundwater pumping for irrigating major crops in trans indo-gangetic plains of India. Clim. Chang. 136, 265–279. https://doi.org/10.1007/s10584-016-1624-2.

Pellegrini, P., Fernández, R.J., 2018. Crop intensification, land use, and on-farm energy-use efficiency during the worldwide spread of the green revolution. Proc. Natl. Acad. Sci. 115, 2335.

Rao, N.D., et al., 2018. Healthy, affordable and climate-friendly diets in India. Glob. Environ. Chang. 49, 154–165. https://doi.org/10.1016/j.gloenvcha.2018.02.013.

Scott, C.A., 2011. The water-energy-climate nexus: resources and policy outlook for aquifers in Mexico. Water Resour. Res. 47. https://doi.org/10.1029/2011WR010805.

Shah, T., Giordano, M., Mukherji, A., 2012. Political economy of the energy-groundwater nexus in India: exploring issues and assessing policy options. Hydrogeol. J. 20, 995–1006. https://doi.org/10.1007/s10040-011-0816-0.

Siddiqi, Afreen, Wescoat Jr., James L., 2013. Energy use in large-scale irrigated agriculture in the Punjab province of Pakistan. Water Int. 38 (5), 571–586.

Singh, A., 2009. A Policy for Improving Efficiency of Agriculture Pump Sets in India: Drivers, Barriers and Indicators. Climate Strategies, London, UK www.climatestrategies.org.

Srivastava, S., Mathur, V., Sivaramane, N., Kumar, R., Hasan, R., Meena, P., 2013. Unravelling Food Basket of Indian Households: Revisiting Underlying Changes and Future Food Demand.

Tilman, D., Balzer, C., Hill, J., Befort, B.L., 2011. Global food demand and the sustainable intensification of agriculture. Proc. Natl. Acad. Sci. U. S. A. 108, 20260–20264.

Vetter, S.H., Sapkota, T.B., Hillier, J., Stirling, C.M., Macdiarmid, J.I., Aleksandrowicz, L., Green, R., Joy, E.J., Dangour, A.D., Smith, P., 2017. Greenhouse gas emissions from agricultural food production to supply Indian diets: implications for climate change mitigation. Agric. Ecosyst. Environ. 237, 234–241.

Wada, Yoshihide, Beek, LPHv, Bierkens, Marc F.P., 2012. Nonsustainable groundwater sustaining irrigation: a global assessment. Water Resour. Res. 48 (6).

Yan, X.O., Toshimasa, Akimoto, Hajime, 2003. Development of region-specific emission factors and estimation of methane emission from rice fields in the East, Southeast and South Asian countries. Glob. Chang. Biol. 9, 237–254.

Zhang, J., et al., 2014. Model of evapotranspiration and groundwater level based on photovoltaic water pumping system. Appl. Energy 136, 1132–1137. https://doi.org/10.1016/j.apenergy.2014.05.045.

Zhu, T., Ringler, C., Cai, X., 2007. Energy price and groundwater extraction for agriculture: exploring the energy-water-food nexus at the global and basin levels. International Conference of Linkages Between Energy and Water Management for Agriculture in Developing Countries, Hyderabad, India.